Eco-efficient Flight Trajectory Exploration by Using the Chemistry-climate Model EMAC

Hiroshi Yamashita and Bastian Kern
Institute of Atmospheric Physics, German Aerospace Center (DLR)

DLR

Deutsches Zentrum
für Luft- und Raumfahrt
German Aerospace Center

DLR at a glance

- Research institution
- Space Administration
- Project Management Agency

Locations and employees

More than 9000 employees work in 54 institutes and facilities at 30 sites across Germany.

International offices in Brussels, Paris, Tokyo and Washington D.C.

National and international networking

Clients and partners: Governments and ministries, agencies and organisations, industry and business, science and research

Areas of research:

- Aeronautics
- Space research and technology
- Transport
- Energy
- Security (cross-sectoral area)
- Digitalisation (cross-sectoral area)

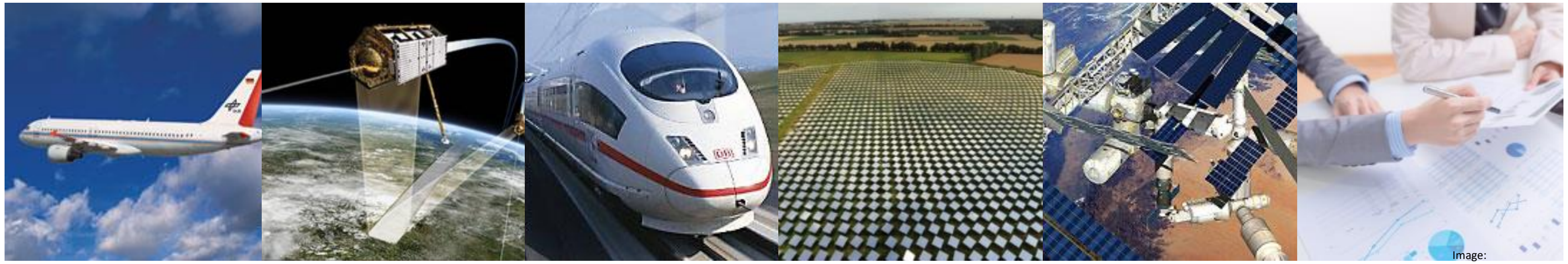
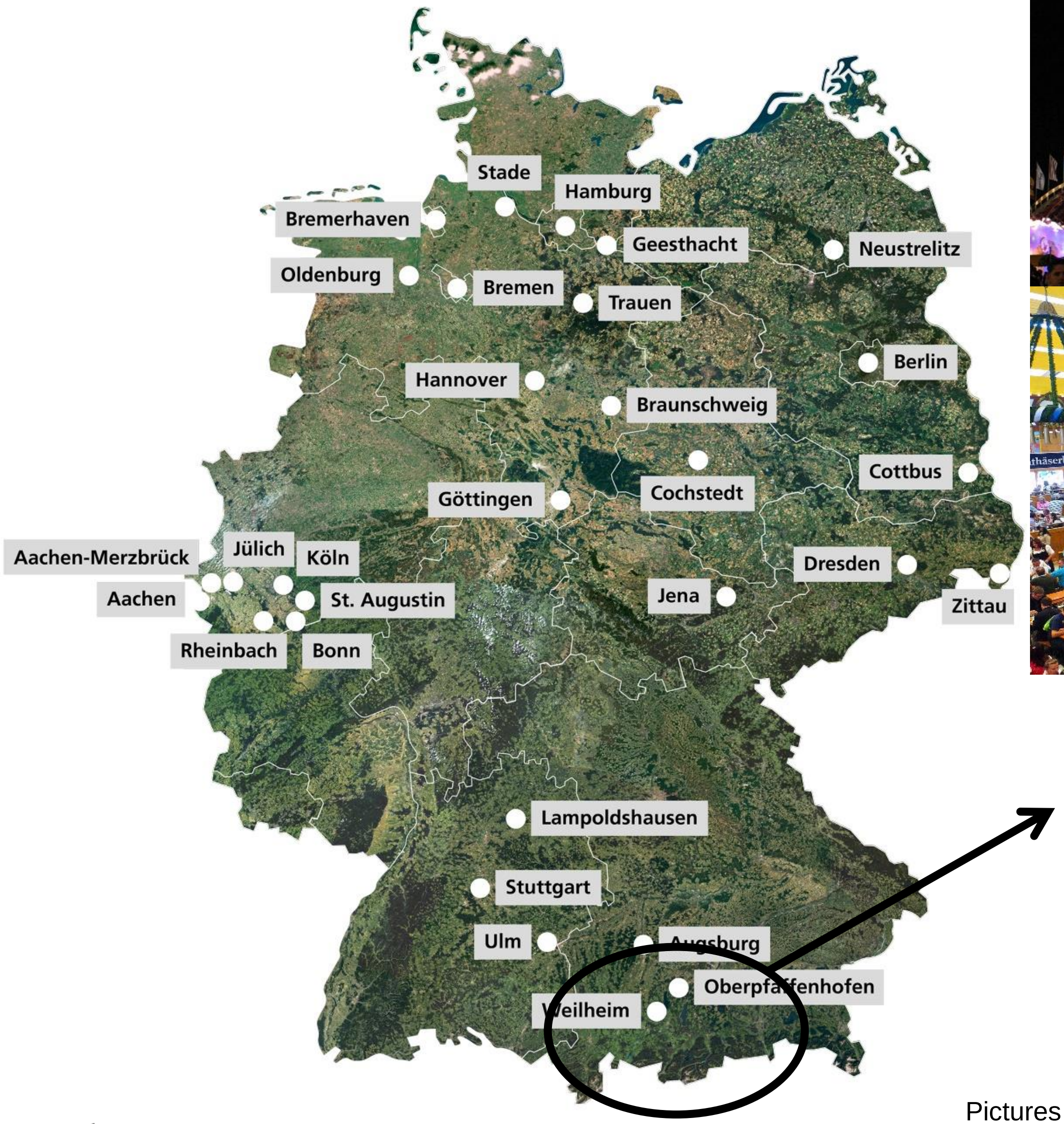


Image: Nonwarit/Fotolia

DLR Oberpfaffenhofen



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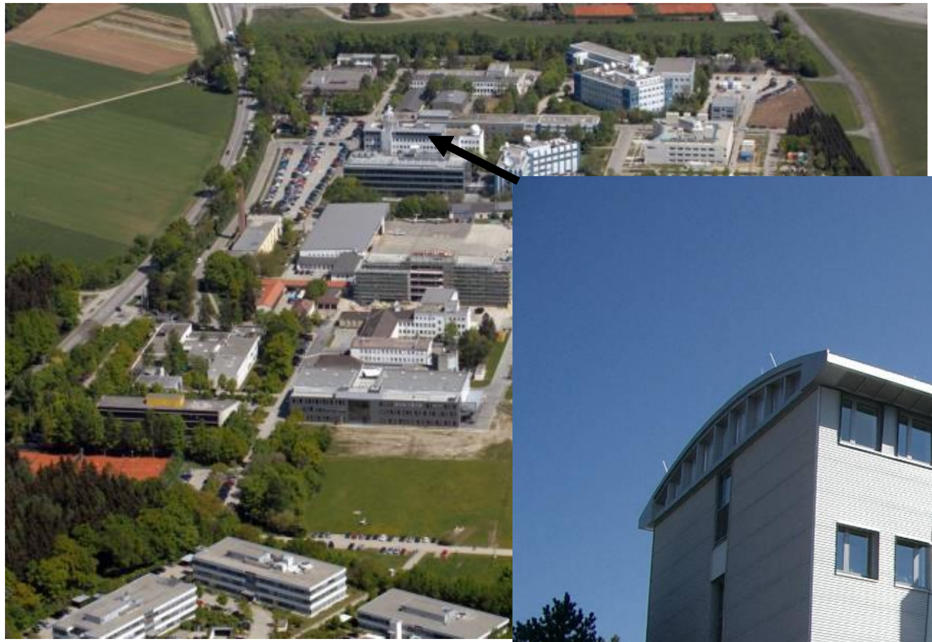
DLR Oberpfaffenhofen

Employees: 1,959

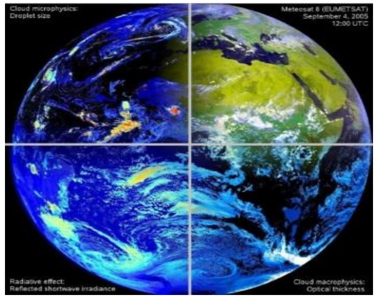
Area: 249,508 m²

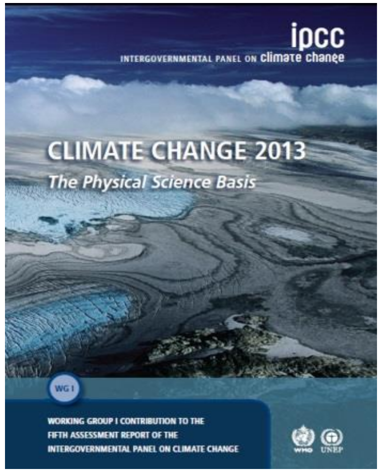
Research institutes and facilities:

- Microwaves and Radar Institute
- Institute of Communications and Navigation
- Remote Sensing Technology Institute
- Institute of Atmospheric Physics
- Institute of Robotics and Mechatronics
- Institute of System Dynamics and Control
- German Remote Sensing Data Center
- Flight Experiments Facility
- Complex Plasmas Research Group
- Space Operations and Astronaut Training
- Galileo Control Centre



The DLR Institute of Atmospheric Physics





Physics and chemistry of the global atmosphere: 0-120 km altitude

Socially relevant issues related to the atmosphere in aviation, space travel, transport and energy

Climate protection, mobility of the future, digitalization & artificial intelligence, energy system transformation

Both basic and application-oriented questions

Broad spectrum of methods

Internationally competitive and in some areas internationally leading

Competent contact for DLR, society, industry and politics

The institute at a glance

Founded 1.7.1962 (1924)

End of 2019 150 employees (51f, 99m)

thereof ~ 37 PhD students

18 Lectureships/professorships at 9 universities/colleges

Overall budget 2019: 18,8 M€ (~ 2256 M¥)

Basic funding : 13,2 M€

(48% Aerospace, 39% Aviation, 11% Traffic, 2% Energy)

Third-party funds : 5,6 M€ (ESA, EU/ERC, BMBF, BMWi, DFG, HGF, Airbus,…)

Organization

Institute of Atmospheric Physics
Prof. Markus Rapp
Director

Logistics
Sonja Koch
Stefanie Zähnle
Controlling

Quality Management
Dr. Arthur Schady

Earth System Modelling
a)
Prof. Robert Sausen

- **YIG MACClim**
  J.-Prof. Hella Garny

ESM – Evaluation and Analysis
Prof. Veronika Eyring

Atmospheric Trace Species
Dr. Anke Roiger

Cloud Physics
Prof. Christiane Voigt

- **Passive Cloud-Remote Sensing**
  Dr. Luca Bugliaro

Transport Meteorology
Dr. Thomas Gerz

Lidar
Dr. Andreas Fix

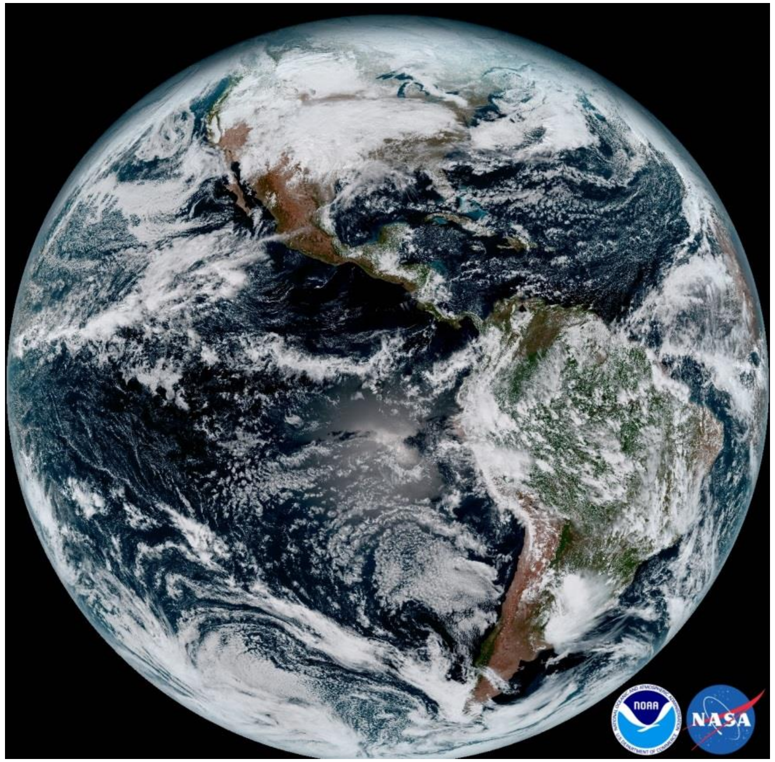
- **Lidar/Radar-Synergy**
  Dr. Silke Groß

a) New appointment as of 01.07.2021; W2 appointment procedure with LMU ongoing

close cooperation with

(Numerical) Modelling in a nutshell

- There is no second Earth (to experiment with)



NOAA/NASA
https://www.nasa.gov/image-feature/new-weather-satellite-sends-first-images-of-earth

Wikimedia, user Hellerick
https://commons.wikimedia.org/wiki/File:Division_of_the_Earth_into_Gauss-Krueger_zones_-_Globe.svg

(Numerical) Modelling in a nutshell

- There is no second Earth (to experiment with)
- A mathematical model

  → based on physical equations

  → coupled system of (non-linear) partial differential equations

  → solved numerically on a “supercomputer”

https://www.dkrz.de/about/media/galerie/Media-DKRZ/hlre-3

(Numerical) Modelling in a nutshell

- There is no second Earth (to experiment with)
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  → based on physical equations

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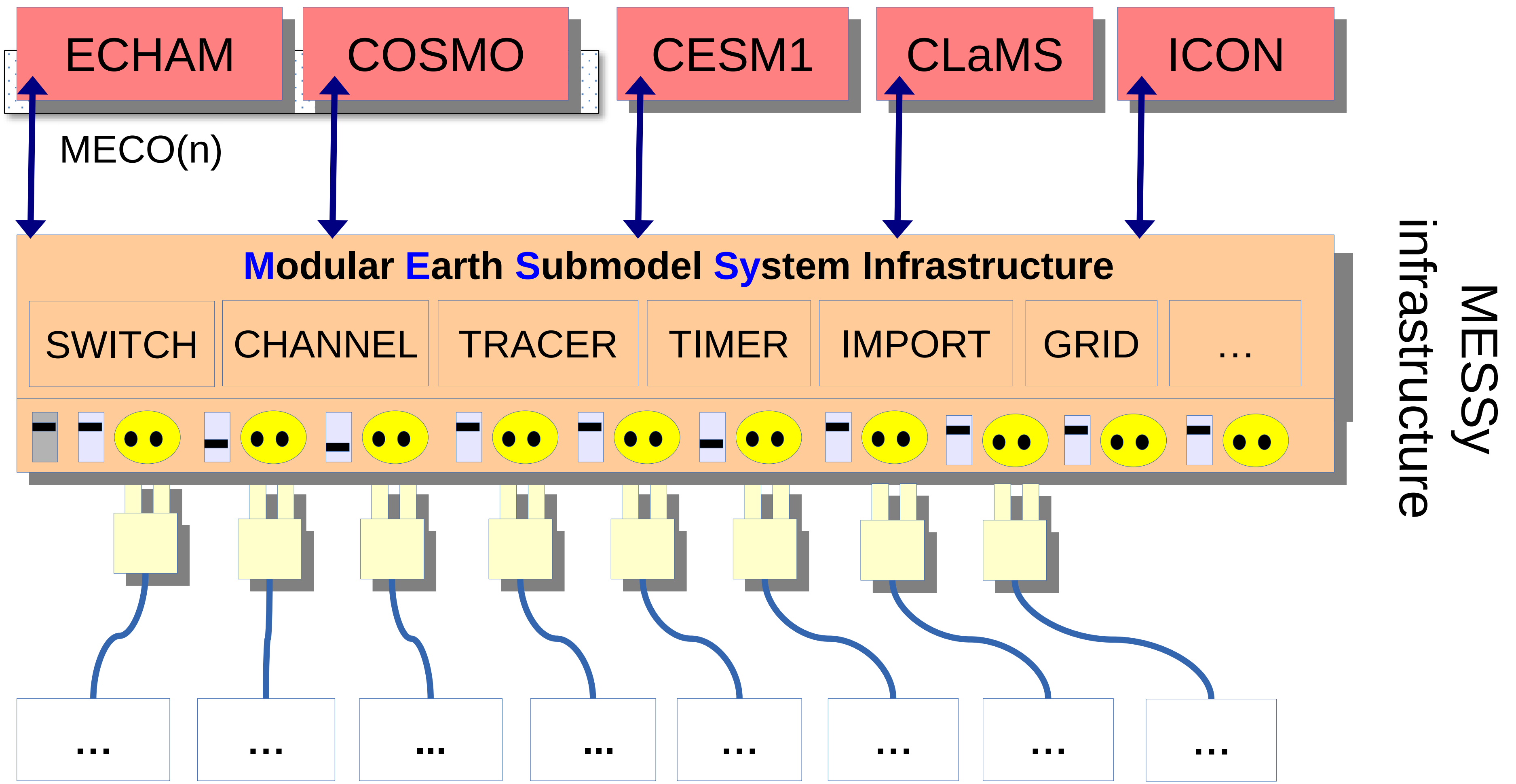
- Climate projection (vs. weather forecast)
  - no forecasts, but climate projections → statistical analyses
  - boundary value problem (vs. initial value problem)
  - model produces realistic weather systems from internal variability

Modular Earth Submodel System (MESSy)

EMAC = **E**CHAM/**M**ESSy **A**tmospheric **C**hemistry



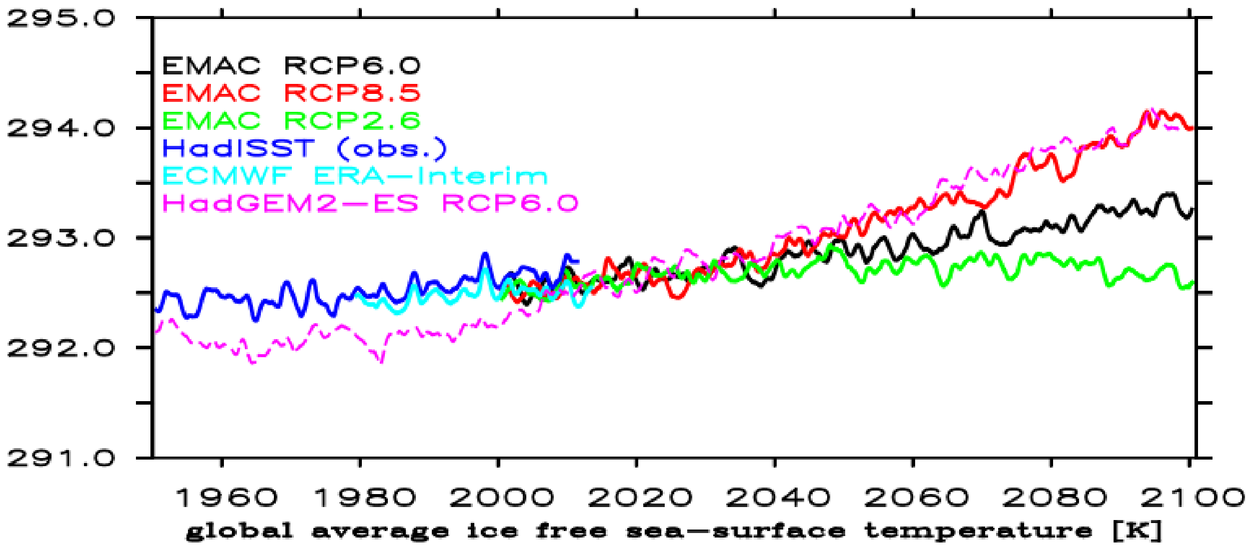
https://www.messy-interface.org/

> 20 partner institutes

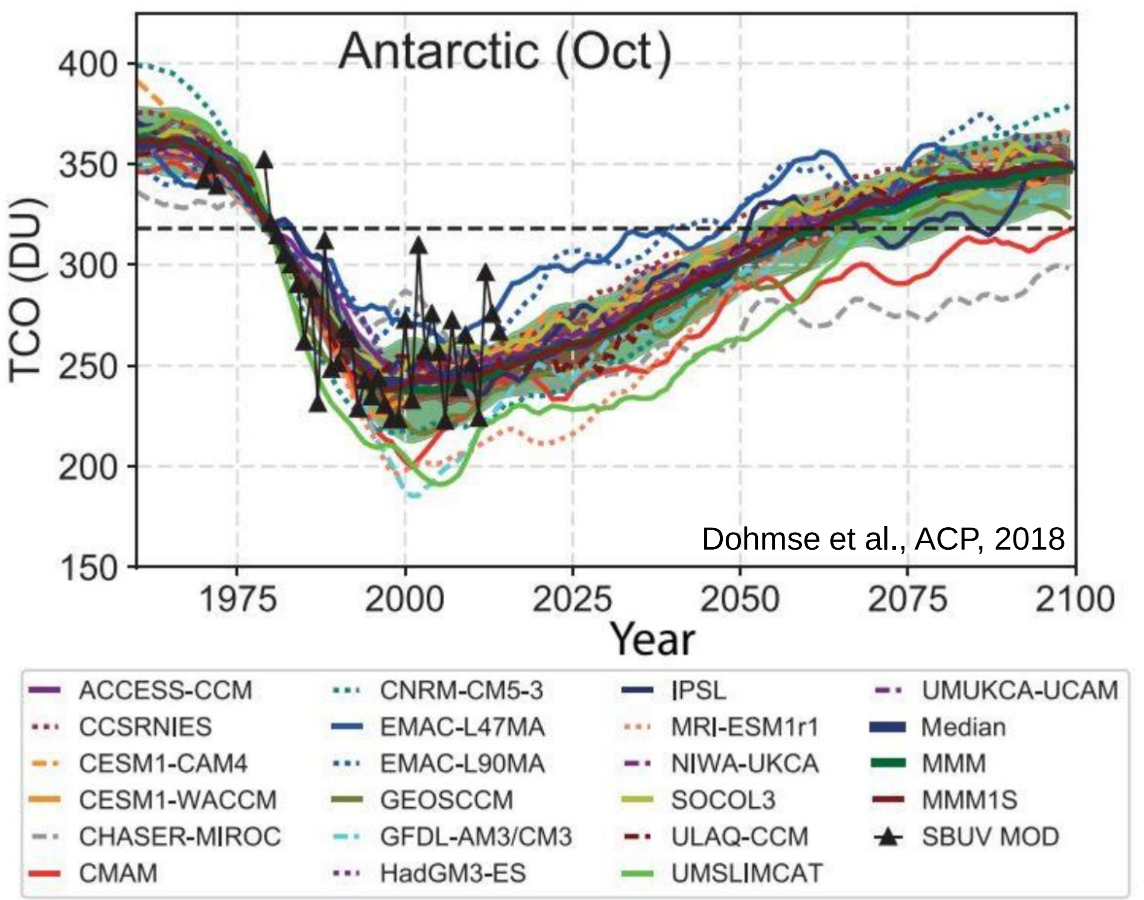
Framework to couple scientific codes to numerical weather prediction and climate models

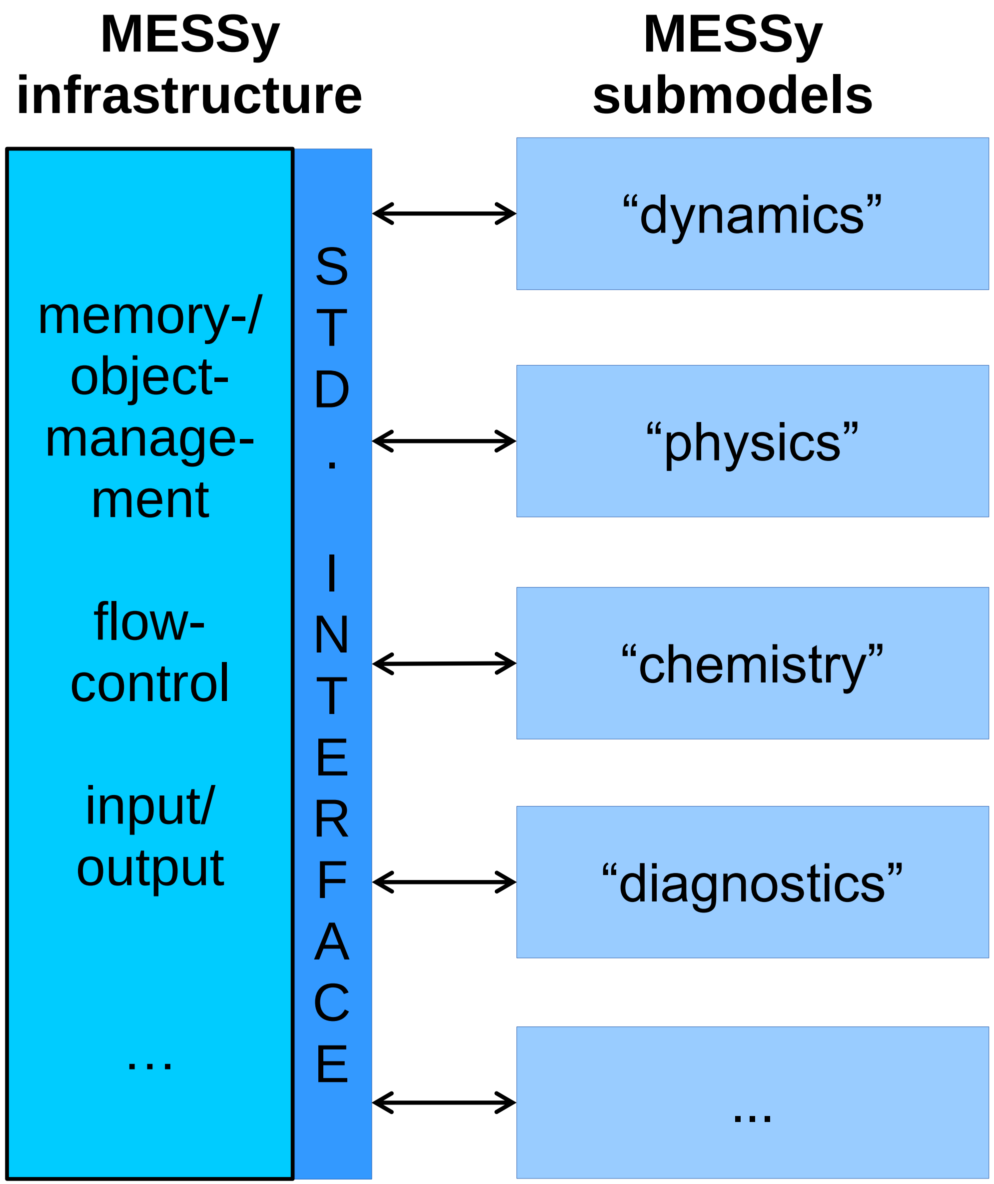
Climate projections with EMAC

- Model simulations with 2 PByte output
- Contribution to Chemistry Climate Initiative (CCMI)
- Data for WMO Ozone Assessment and Intergovernmental Panel on Climate Change (IPCC)



Total ozone column (DU), Antarctic, October





"communication" between individual components through mutual access of distributed objects via standard interfaces

expandability without intervention in other components

- scalable development
- coexistence of alternatives

→ **"community"-ansatz**

2nd part

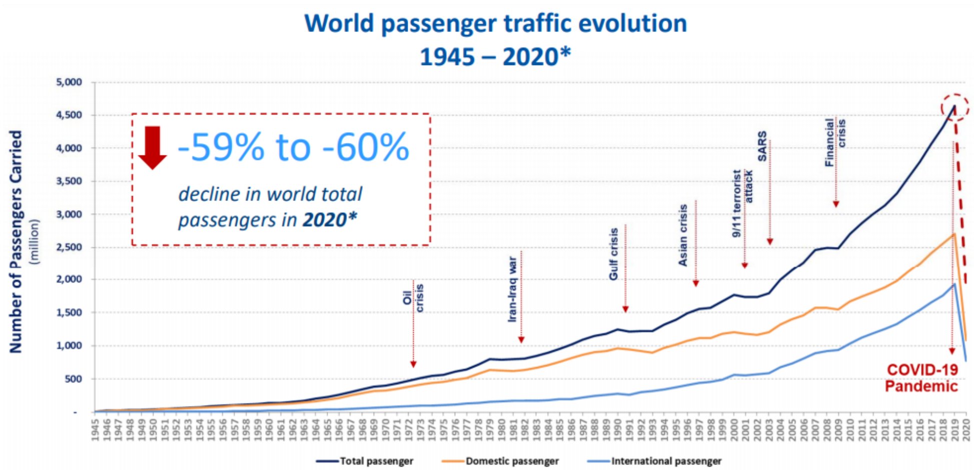
Application study

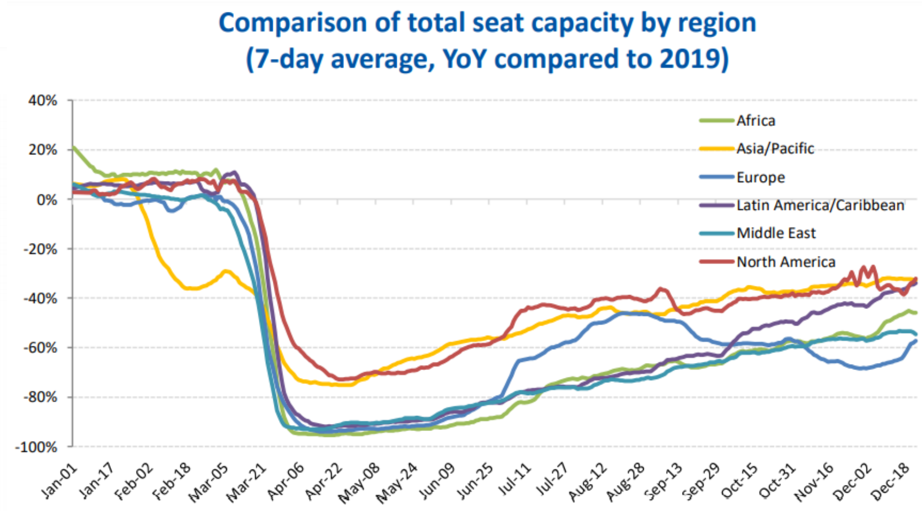
Contents

- Aviation and climate impact
- Climate-optimized routing
- Research objectives and methodologies
- EMAC/AirTraf model components
- 1-day air traffic simulations over the North Atlantic with different aircraft routing options
- Multi-objective optimization in EMAC/AirTraf
- Summary – research topics for further collaborations

Growth of air transport

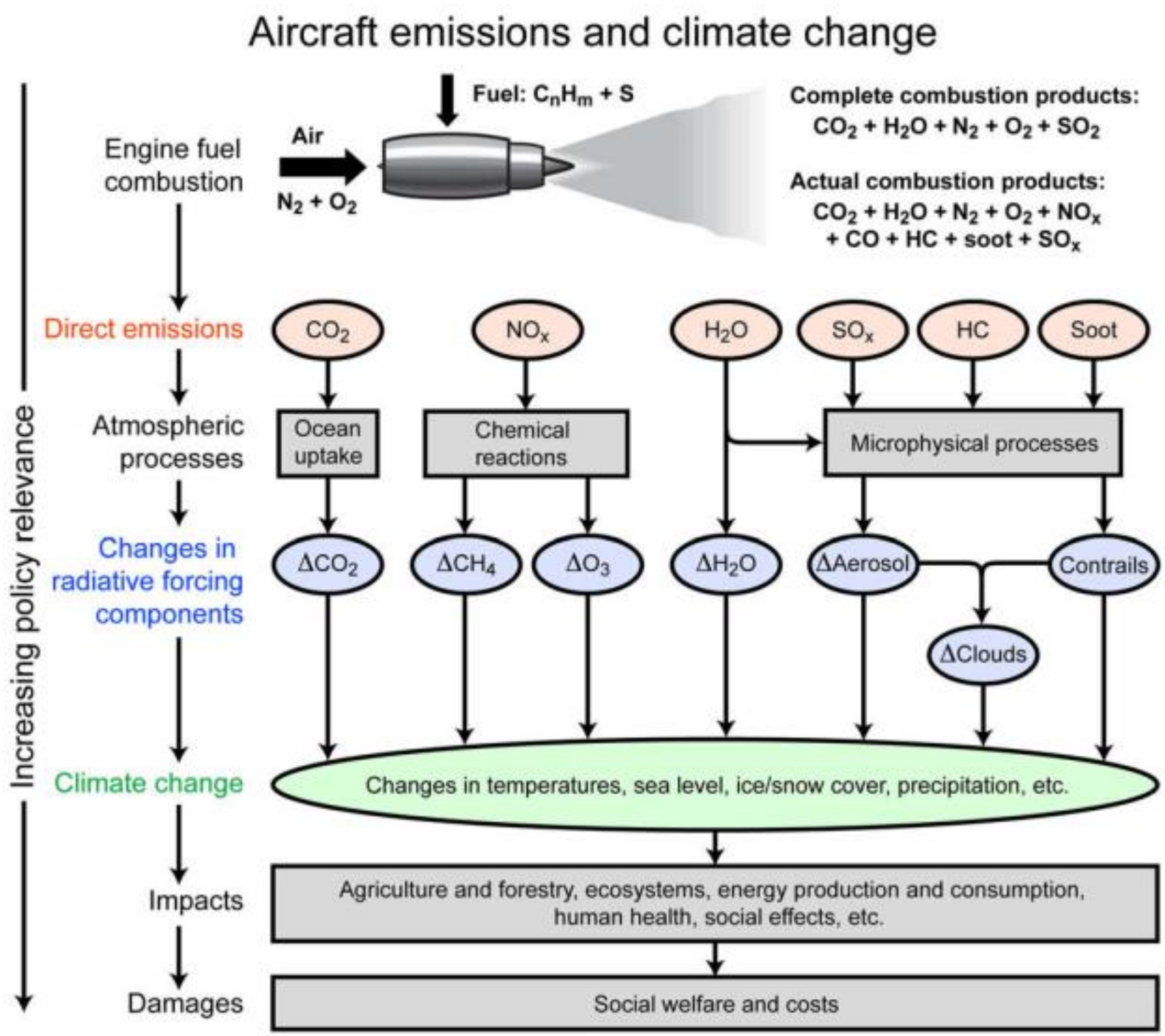
- Strong growth in air traffic: +5 %/yr (1945 - 2019)
- World passenger traffic collapsed due to COVID-19 Pandemic, but it is recovering





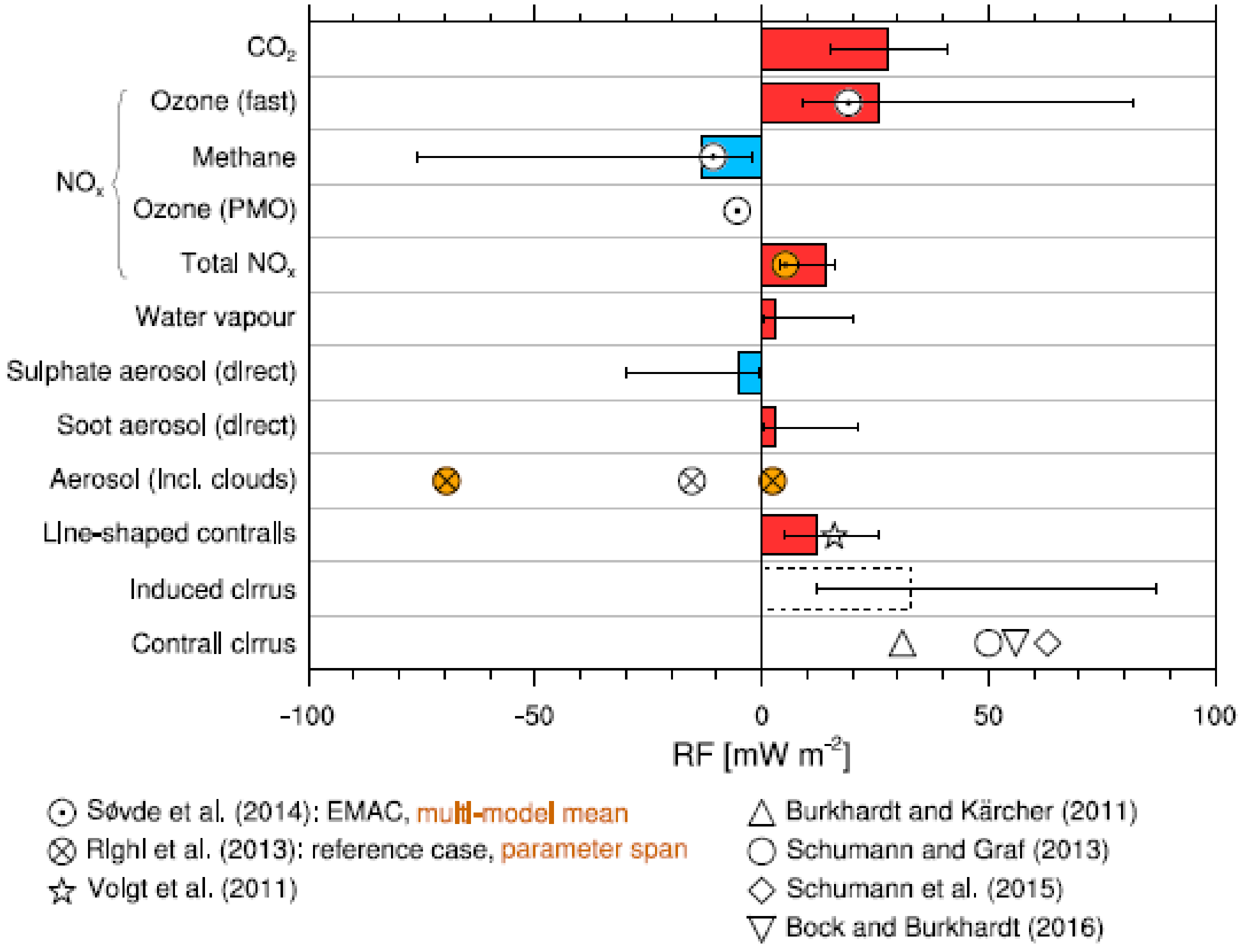
ICAO 2020

Aviation emissions and climate change



Lee et al. 2009

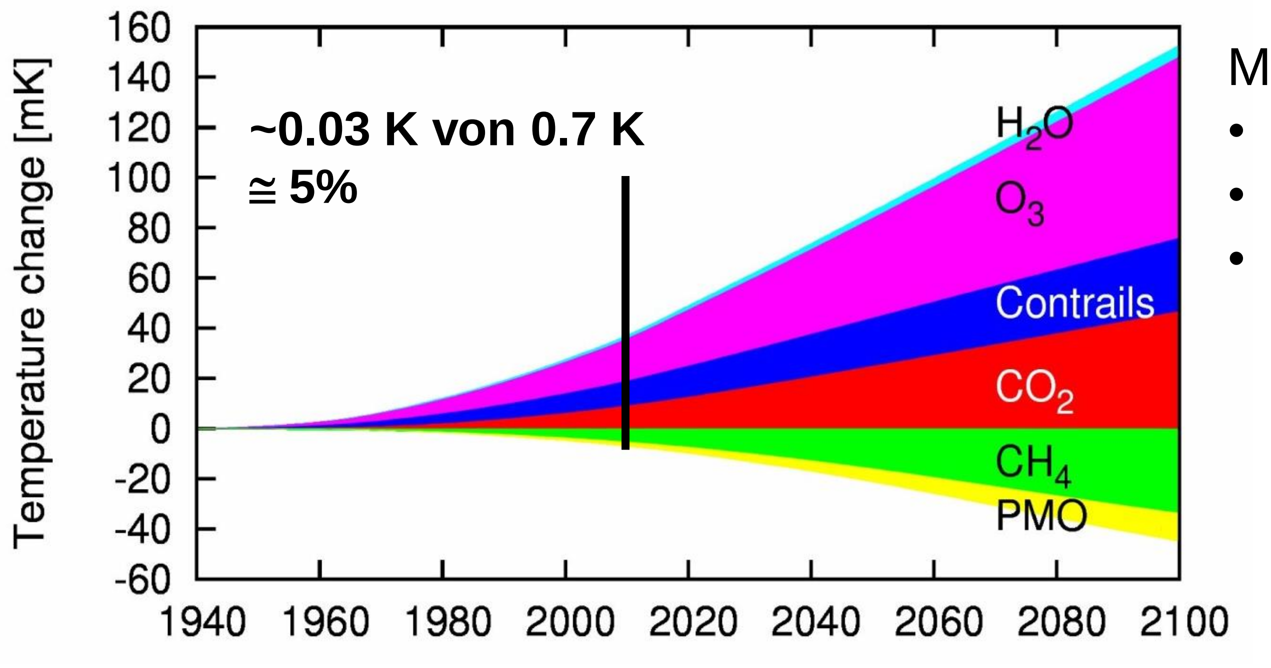
Aviation and radiative forcing for 2005



Grewe et al. 2017

Impact of aviation on global surface temperatures

- Air traffic contributes around 5 % to anthropogenic warming



Main contributions from:

- CO_2
- Contrails
- NO_x (O_3 and CH_4)

PMO=„Primary mode ozone“
Results from less $CH_4 \Rightarrow$ less $HO_2 \Rightarrow$ less O_3 production

Grewe et al. 2016

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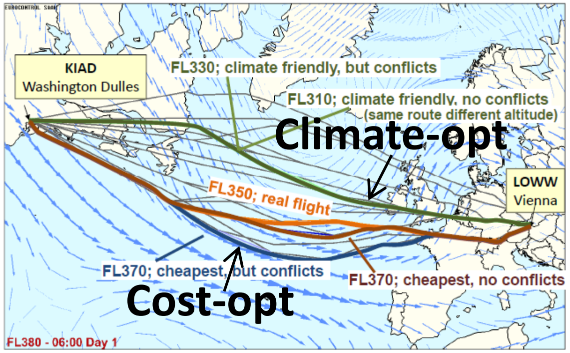
Climate-optimized routing

- "Climate cost function (CCF) identifies climate sensitive regions for emissions (CO_2, H_2O, ozone, Methane, contrails) and estimates climate impacts

- Climate-optimal route was calculated by air traffic simulator SAAM by Eurocontrol:
  - –19 % less climate impact
  - 1 % longer flight time
  - 14 % more fuel
  - 22 % more NO_x
  - 10 % more costs

Example of route options for one flight from Washington to Vienna (AGWP20)



Frömming, et al. 2013
Grewe, et al. 2014, 2017
Matthes, et al. 2012,2017

Research objectives

- To investigate an eco-efficient aircraft routing strategy that reduces the climate impact of global air traffic over the next few decades
- To estimate its mitigation gain for different aircraft routing strategies

Methodologies

- **Chemistry-climate model EMAC (ECHAM5/MESSy 2.54)** Roeckner et al., 2006; Jöckel 2010, 2016
- **Submodel AirTraf 2.0** Yamashita, Kern et al. 2020
  - 9 routing strategies (called options)
  - Trajectory optimization (3D)
  - Geographic location, altitude, time of released non-CO_2 emissions/contrails are considered
  - Simplifications:
    - Only cruise flight phase
    - No potential conflicts of flight trajectories
    - No operational constraints from ATC

Aircraft routing options

0 - **Great circle**
1 - **Flight time**
2 - **Fuel use**
3 - **NO_x emission**
4 - **H_2O emission**
5 - **Contrail formations**
6 - **Simple operating cost**
7 - **Cash operating cost**
8 - **Climate impact**

EMAC/AirTraf model components

Base model

ECHAM5/MESSy 2.54 (EMAC)

Roeckner et al., 2006, Jöckel 2010, 2016

Submodel AirTraf 2.0

Aviation data

- ICAO engine performance data
- Aircraft data (BADA 3.9)
- Flight plan, fuel price, etc.

Fuel/emissions calc.

- Total energy model
- DLR fuel flow correlation method

Deidewig 1996, Schaefer 2012

Optimizer

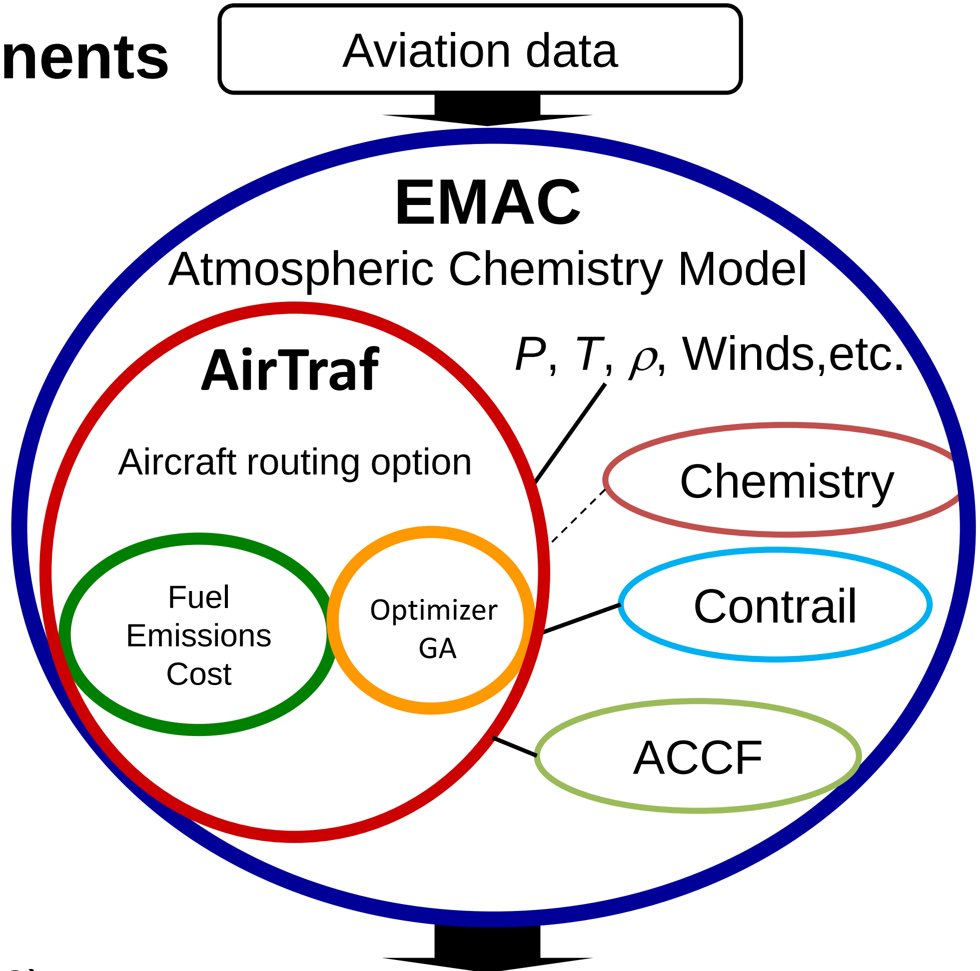
- Genetic algorithms (ARMOGA1.2.0)

Sasaki, 2009

Coupled submodels

- CONTRAIL 1.0
- ACCF 1.0

Van Manen, 2017,2019; Yin, 2018,2020



- Optimized flight trajectories
- Flight performance measures:

- Flight distance, flight time, fuel use, NO_x emission, H_2O emission, contrail distance, operation cost, climate impacts (ATR20s)

- Radiative forcing (surface temperature change)

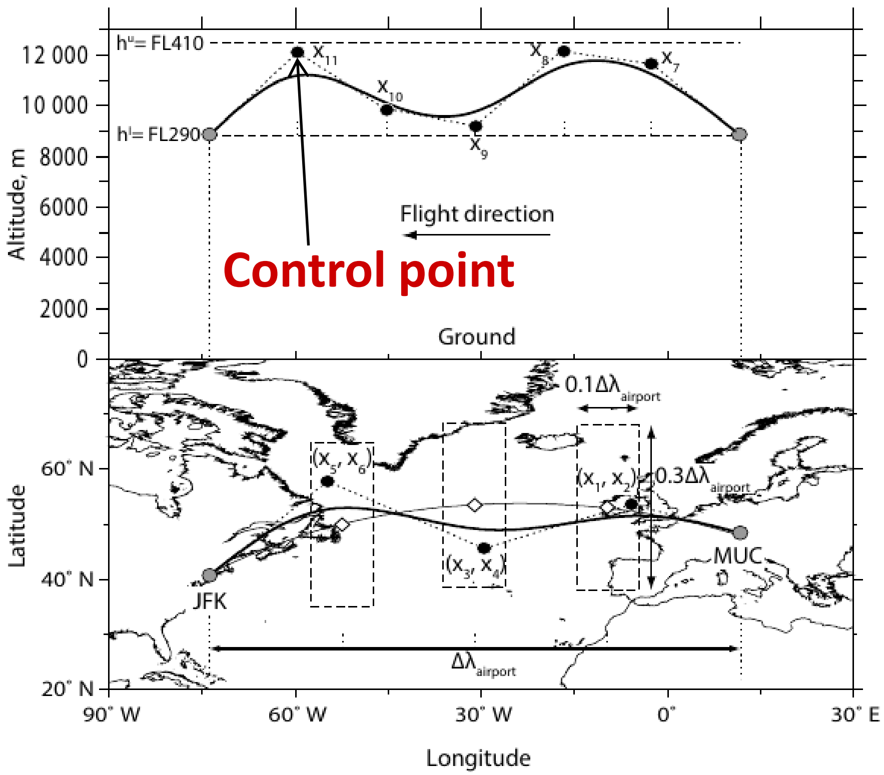
Flight trajectory optimization

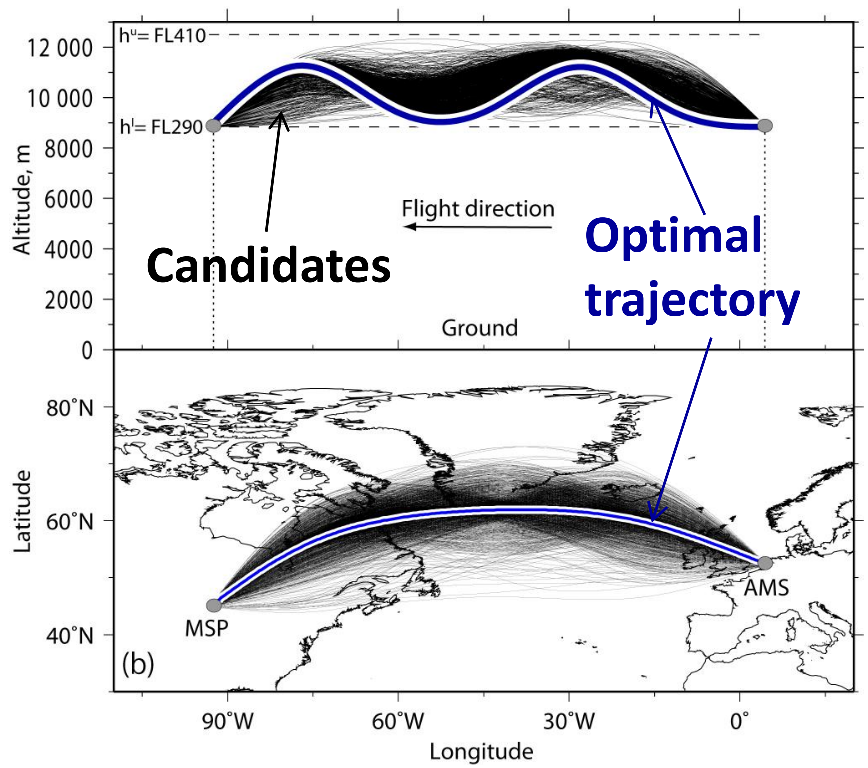
- A trajectory (candidate) is created by B-spline curve with 11 design variables: **6 (geographical location), 5 (altitude)**
- Waypoints are automatically generated
- GA evaluates single objective function and finds out one optimal trajectory to minimize objective function value

Objective function

$$\left.\begin{aligned} \text{Minimize} \quad & f \\ \text{Subject to} \quad & x_j^l \leq x_j \leq x_j^u, \quad j = 1, 2, \cdots, n_{\text{dv}} \end{aligned}\right\}$$

Yamashita et al. 2016





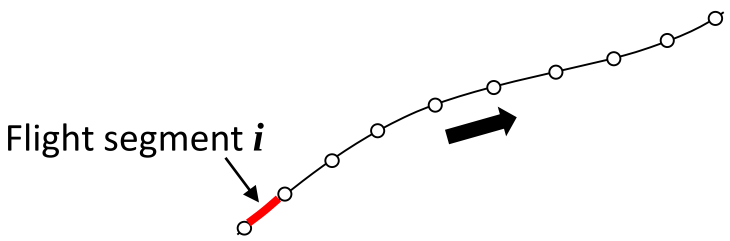
Formulations of objective functions

- **Cost option**
  - Min. Cash Operating Cost (international flights [USD]) Liebeck, 1995

$$f = \mathrm{COC} = C_{\text{flightcrew}} + C_{\text{cabincrew}} + C_{\text{landing}} + C_{\text{navigation}} + C_{\text{fuel}} + C_{\text{airframe}} + C_{\text{engine}}$$

- **Climate option**
  - Submodel ACCF 1.0
  - Min. climate impact over 20 yrs [K] estimated by algorithmic Climate Change Functions aCCFs Van Manen, 2017,2019; Yin, 2018,2020

$$\begin{aligned}
\mathrm{ATR20}_{\mathrm{O_3},i} &= \mathrm{aCCF}_{\mathrm{O_3},i} \times \mathrm{NO}_{x,i} \times 10^{-3},\\
\mathrm{ATR20}_{\mathrm{CH_4},i} &= \mathrm{aCCF}_{\mathrm{CH_4},i} \times \mathrm{NO}_{x,i} \times 10^{-3},\\
\mathrm{ATR20}_{\mathrm{H_2O},i} &= \mathrm{aCCF}_{\mathrm{H_2O},i} \times \mathrm{FUEL}_i,\\
\mathrm{ATR20}_{\mathrm{CO_2},i} &= \mathrm{aCCF}_{\mathrm{CO_2}} \times \mathrm{FUEL}_i,\\
\mathrm{ATR20}_{\mathrm{contrail},i} &= \mathrm{aCCF}_{\mathrm{contrail},i} \times \mathrm{PCC}_{\mathrm{dist},i},
\end{aligned}$$



$$\mathrm{ATR20}_{\mathrm{total},i} = \mathrm{ATR20}_{\mathrm{O_3},i} + \mathrm{ATR20}_{\mathrm{CH_4},i} + \mathrm{ATR20}_{\mathrm{H_2O},i} + \mathrm{ATR20}_{\mathrm{CO_2},i} + \mathrm{ATR20}_{\mathrm{contrail},i},$$

$$f = \sum_{i=1}^{n_{\mathrm{wp}}-1} \mathrm{ATR20}_{\mathrm{total},i},$$

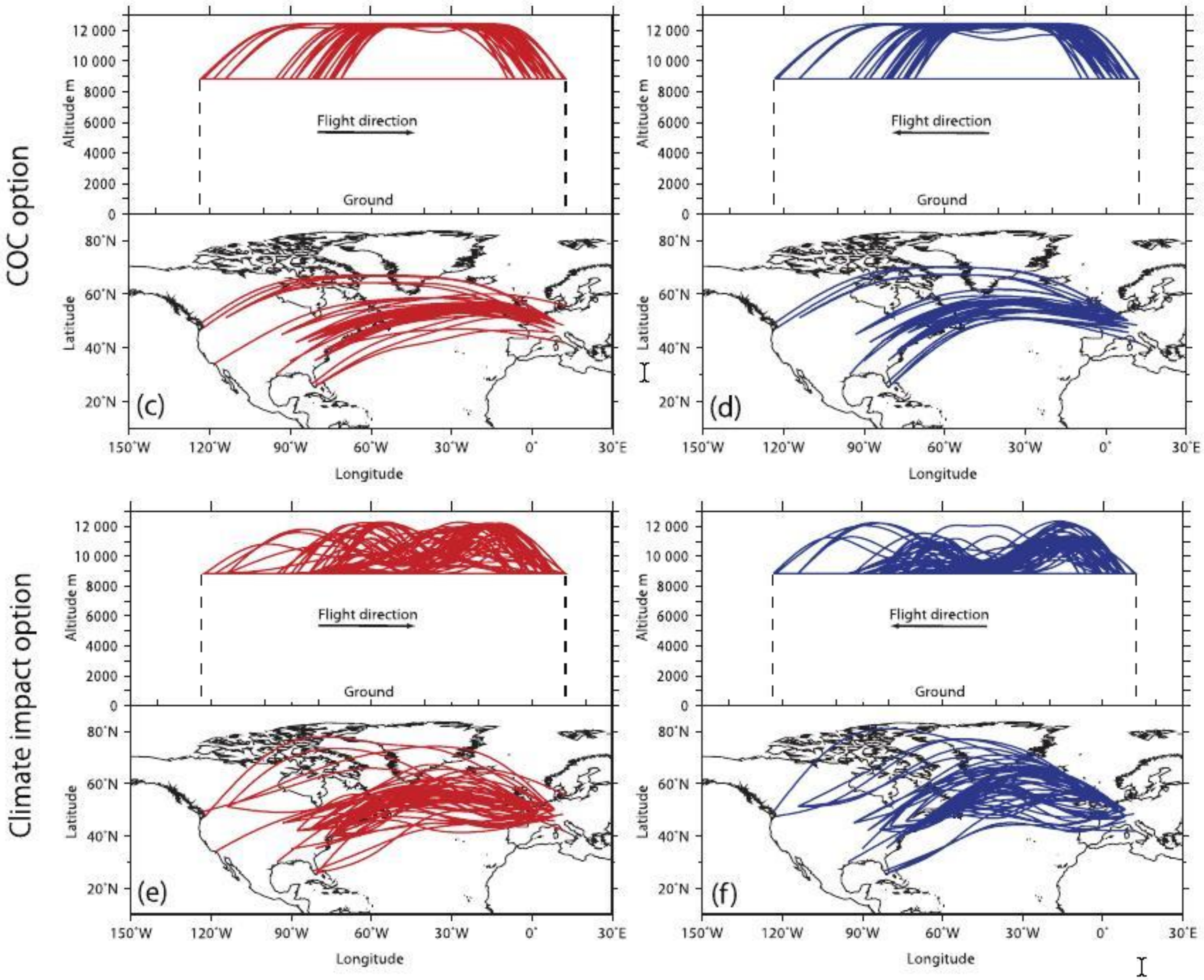
1-day air traffic simulations over the North Atlantic

Routing options	Great circle	Cost/Climate/Others options
ECHAM5 Resolution	T42/L31ECMWF (2.8° × 2.8°)	
Duration / Time step	Dec.01.2015 - Dec.02.2015 / 12 min	
Waypoints	101	
Flight altitude change	Fixed FL350	FL290 - FL410
Flight plan	103 Transatlantic flights by REACT4C Project (Eastbound 52/Westbound 51)	
Aircraft / Engine type	A330-301 / CF6-80-E1-A2 (2GE051)	
EIH_2O [g(H_2O)/kg(fuel)]	1,230 (IPCC 1999)	
Load factor	0.62 (ICAO 2009)	
Fuel price [USD/USG]	1.545 (IATA 2017)	
Unit time cost [USD/h]	2710.0 (Boeing 2015)	
Mach number	0.82 (A330-301, Eurocontrol 2011)	
Optimization	–	Min. f **(single-objective optimization)**
Design variable	–	11 (Location 6/Altitude 5)
Generation number	–	100
Population size	–	100

Optimized flight trajectories

Dec. 1 2015, 103 North Atlantic flights (A330-301)

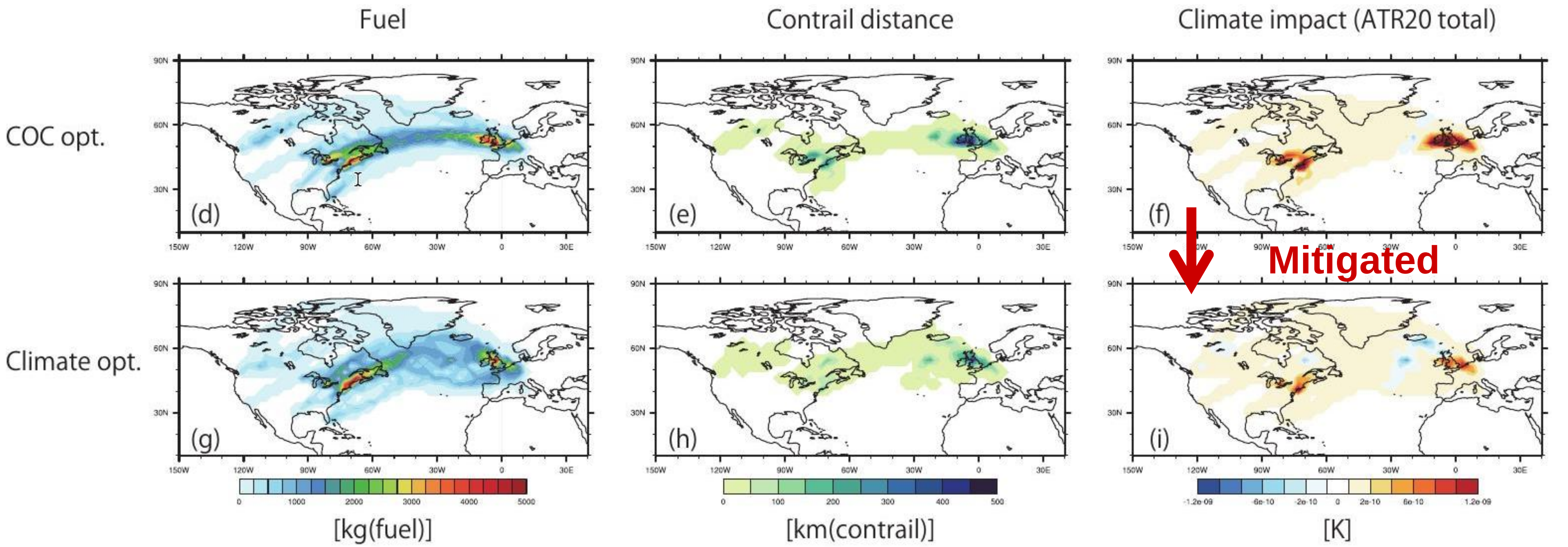
eastbound → **westbound** ←



Yamashita, Kern et al. 2020

Distribution maps

Dec. 1 2015, 103 North Atlantic flights (A330-301)

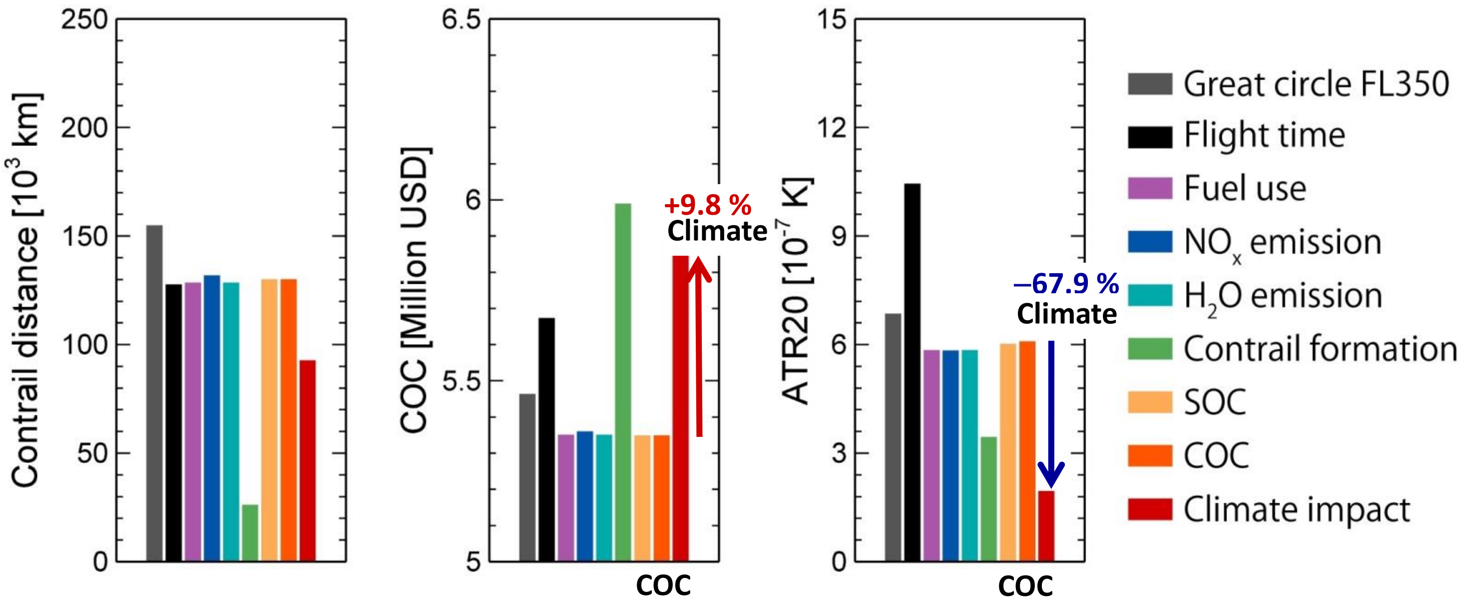


Yamashita, Kern et al. 2020

Flight characteristics
Dec. 1 2015, 103 North Atlantic flights (A330-301)

- Trade-off exists between operational cost and climate impact
- Climate-optimized routing can reduce expected climate impact (ATR20), compared to cost-optimized routing

  - Climate option: –67.9 % ATR20, +9.8 % COC → 0.13 [US Mil$/$10^{-7}$K]



Yamashita, Kern et al. 2020

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Multi-objective flight trajectory optimization in AirTraf

AirTraf initialization

Multi-objective optimization problem

e.g. Min. f_1 = Operating cost

Min. f_2 = Climate impact

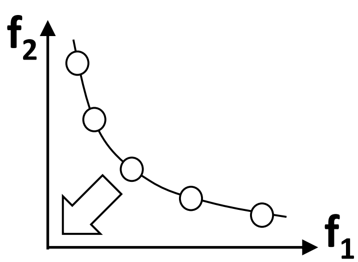
Subject to constraints

Step 1

Multi-objective optimizer

ARMOGA of AirTraf submodel

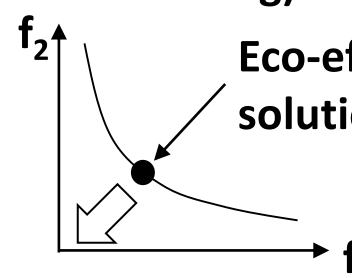
Multiple-trade-off solutions found



Higher-level information

Step 2

Choose one solution (decision-making)



Eco-efficient solution

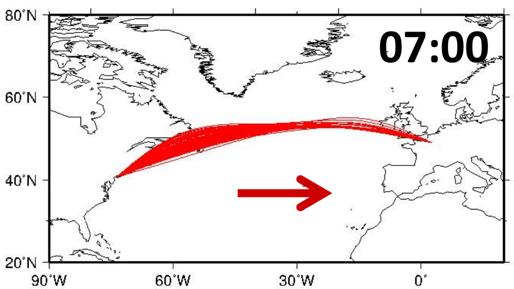
Air Traffic simulations for eco-efficient routing strategy

Deb 2001

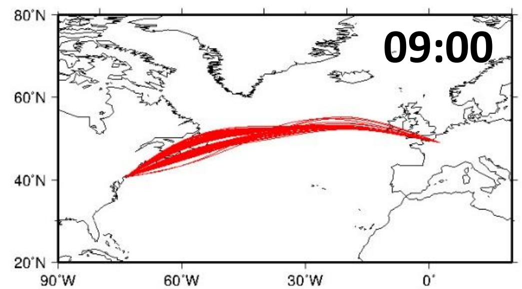
Benchmark test

Min. f_1 = Flight time [s]
Min. f_2 = Fuel use [kg(fuel)]
Min. f_3 = Climate impact (ATR20) [K]
Flight route: from JFK (New York) to CDG (Paris), flight alt. at FL290 (fixed)
Target day: 01 June 2015
Departure time (local time): from 07:00 to 17:00 (every 2h)

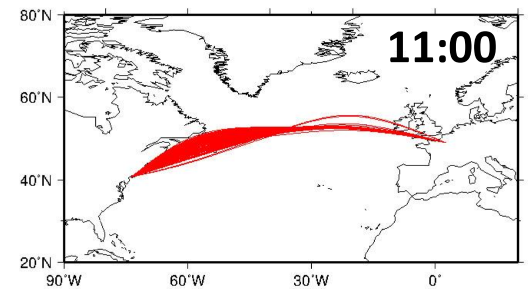
1534 optimal solutions



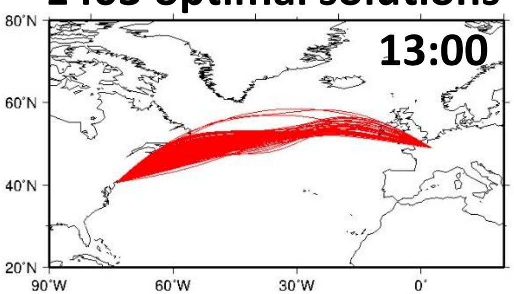
1384 optimal solutions



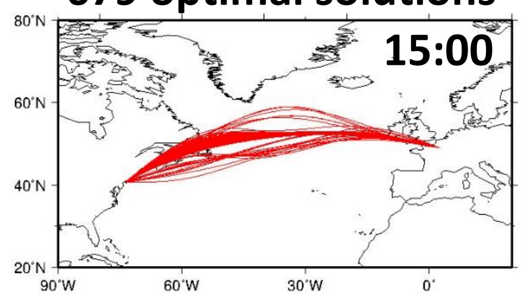
813 optimal solutions



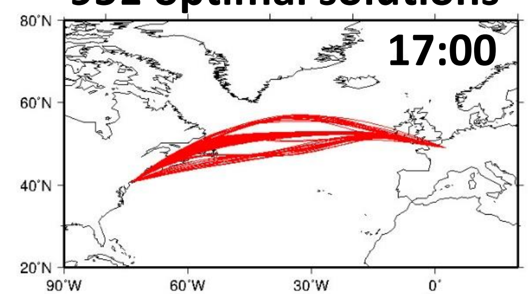
1403 optimal solutions



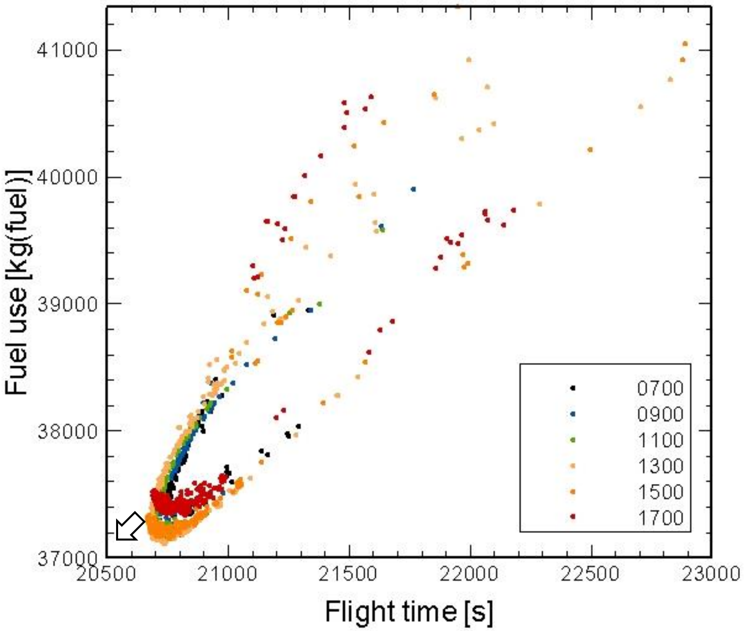
679 optimal solutions

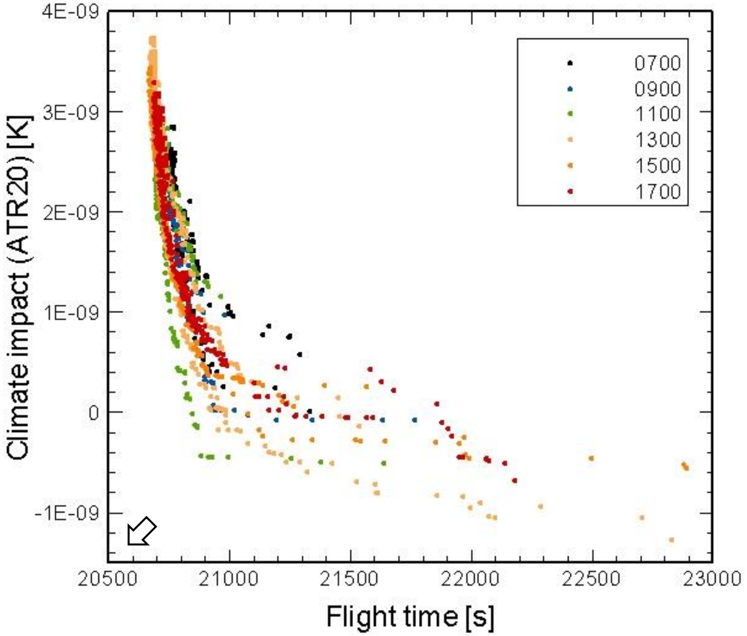


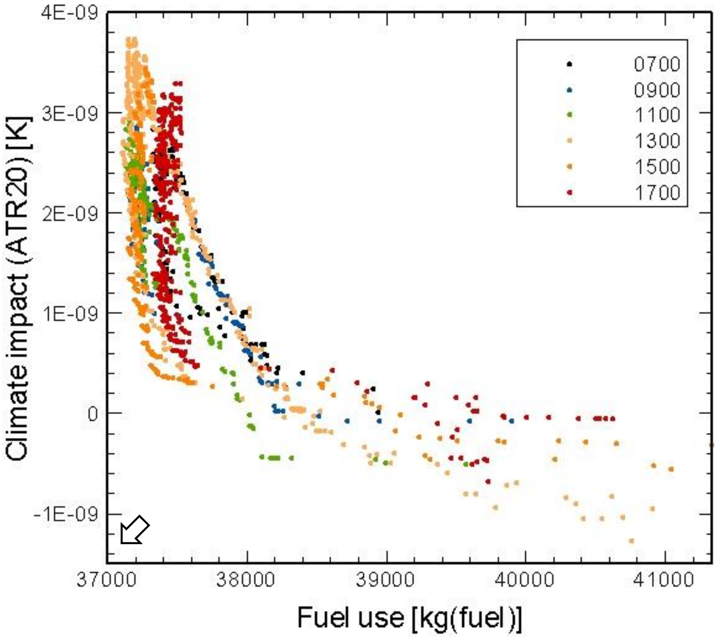
951 optimal solutions



Non-dominated solutions







Summary – research topics for further collaborations

1. To detect some unique points of the nondominated solutions and visualize the structure of nondominated fronts

2. To examine how much nondominated fronts vary under different weather conditions

3. To develop a decision-making method in EMAC/AirTraf